Water Balance Modeling

by

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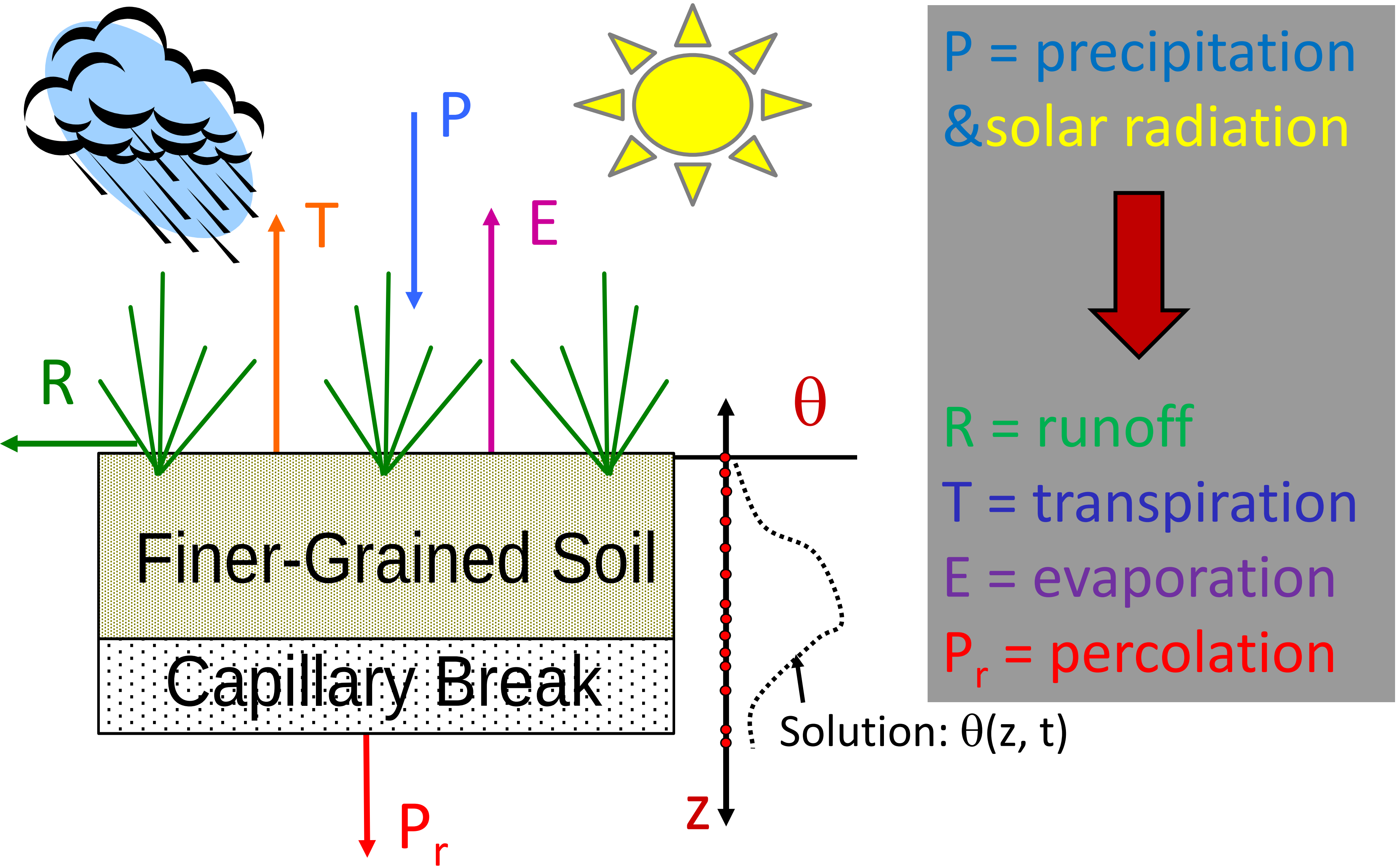
Steps in Water Balance Modeling

1. Develop conceptual model
2. Select software
3. Collect and organize data
4. Implement software (input and run)
5. Evaluate and report on output.

Conceptual Model



Conceptual Model

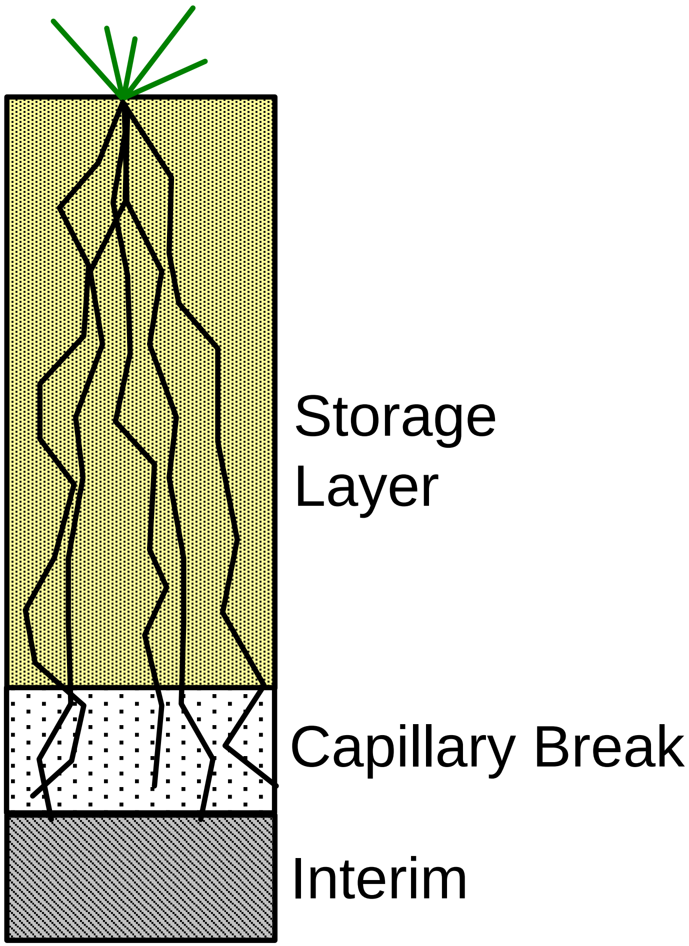
1. **What is the cover profile?**
   - **Monolithic or capillary barrier design**
   - **Layer types and properties**

2. **Vegetated or non-vegetated?**
   - **Vegetation normally required for water management and erosion control**
   - **What type of vegetation? Grasses, shrubs, trees?**

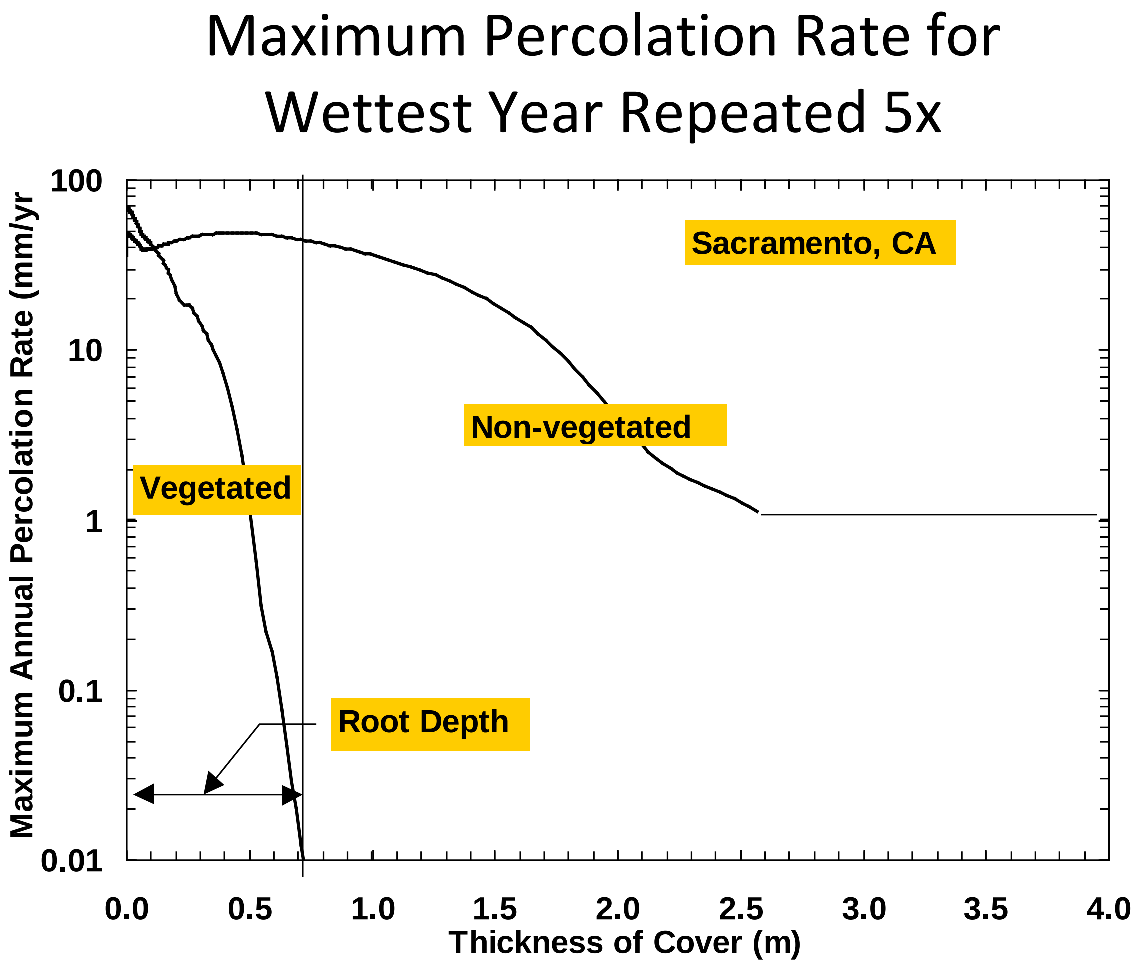
3. **What is the surface boundary?**

   Normally an atmospheric "flux" boundary is used

4. **What is the lower boundary?**
   - **Unit gradient at base**
   - **Include waste?**



Effect of Vegetation



- Parametric simulations conducted by Winkler (1999)
- Illustrates how vegetation pumps water stored within profile.

Basic Model Requirements

- Must simulate unsaturated flow in a rigorous manner (i.e., must solve Richards' equation).
- Must include a surface boundary simulating soil-atmosphere interactions (precipitation, infiltration, evaporation, runoff).
- Must include root water uptake; should be integrated into Richards' equation.
- Must integrate climatic data into the solution.

Modified Richards' Equation

$$\frac{\partial\theta}{\partial t} = \nabla \bullet \left[K_\psi \nabla(z - \psi)\right] - S$$

or

$$C_\psi \frac{\partial\psi}{\partial t} = \nabla \bullet \left[K_\psi \nabla(z - \psi)\right] - S$$

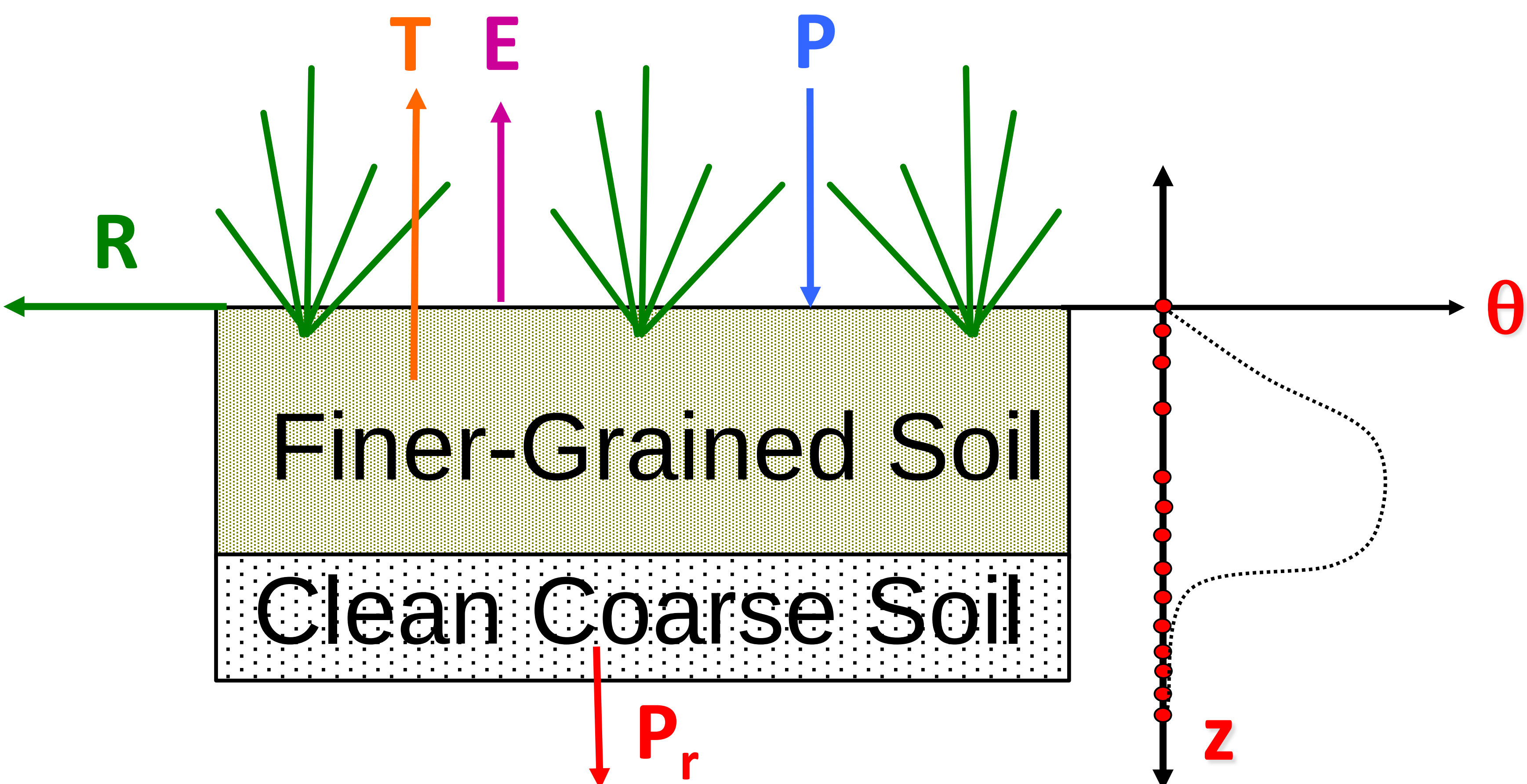
Terms: θ = volumetric water content, t = time, K_ψ = hydraulic conductivity, ψ = matric suction, z = vertical coordinate, C_ψ = specific water capacity, S = sink term for root water uptake.

Key assumptions: isothermal, no volume change, liquid flow only

What Does Richards' Eqn. Do?

$$\frac{\partial\theta}{\partial t} = \frac{\partial K}{\partial z} - \frac{\partial}{\partial z}\left[K_c \frac{\partial\psi}{\partial z}\right] - S$$

Apply boundary conditions and input meteorological, soil, and vegetation inputs. Run to obtain θ(z,t)



Model Selection

Code	Dimensionality	Source
HYDRUS	1, 2, or 3D	www.pc-progress.com (1D free)
LEACHM	1D	http://www.flinders.edu.au/science_engineering/environment/our-school/staff-postgrads/academic-staff/hutson-john/leachm.cfm
SVFLUX	1, 2, or 3D	www.soilvision.com
UNSAT-H	1D	DOS v3.01 (free):http://hydrology.pnl.gov/resources/unsath/unsath.asp Windows v2.04 (free): https://mywebspace.wisc.edu/chbenson/WinUNSATH/
VADOSE/W	1D or 2D	www.geo-slope.ca

More Information on Models

Bohnhoff, G., Ogorzalek, A., Benson, C., Shackelford, C., and Apiwantragoon, P. (2009), Field Data and Water-Balance Predictions for a Monolithic Cover in a Semiarid Climate, *J. Geotech. and Geoenvironmental Eng., 135(3), 333-348.*

Ogorzalek, A., Bohnhoff, G., Shackelford, C., Benson, C., and Apiwantragoon, P. (2007), Comparison of Field Data and Water-Balance Predictions for a Capillary Barrier Cover." *J. Geotech. and Geoenvironmental Eng., 134(4), 470-486.*

Input Data Collection

- Meteorological data – precipitation, temperature, humidity, solar radiation, wind speed, cloud cover etc.
- Plant properties – growing season, root depth vs. time, root density function, leaf area index, plant limiting function parameters (local NRCS).
- Geometry – profile of cover.
- Soil properties – saturated hydraulic conductivity, SWCC parameters (measure in lab).

Meteorological Data

- Data requirements:
  - Precipitation
  - Temperature
  - Relative humidity
  - Wind speed
  - Diffuse solar radiation
  - Cloud cover

- Most projects have incomplete data sets and require that data be supplemented from other sources. Data are listed above in order of importance

Sources of Meteorological Data - 1

NOAA – Regional Climate Centers

http://www.wrcc.dri.edu/rcc.html

- Good historical precipitation data, but requires processing before use.
- Usually more than one station in close proximity, which is good for verification.
- Other data (temperature, solar, etc.) can be limited.
- Fee may be required.

Sources of Meteorological Data - 2

- Bureau of Reclamation Agrimet
- http://www.usbr.gov/pn/agrimet/wxdata.html
  - Contains nearly all required input data
  - Limited in duration and location (PNW)
- Texas Solar Radiation Data

  http://www.me.utexas.edu/~solarlab/tsrdb/tsrdb.html
- National Solar Radiation Data

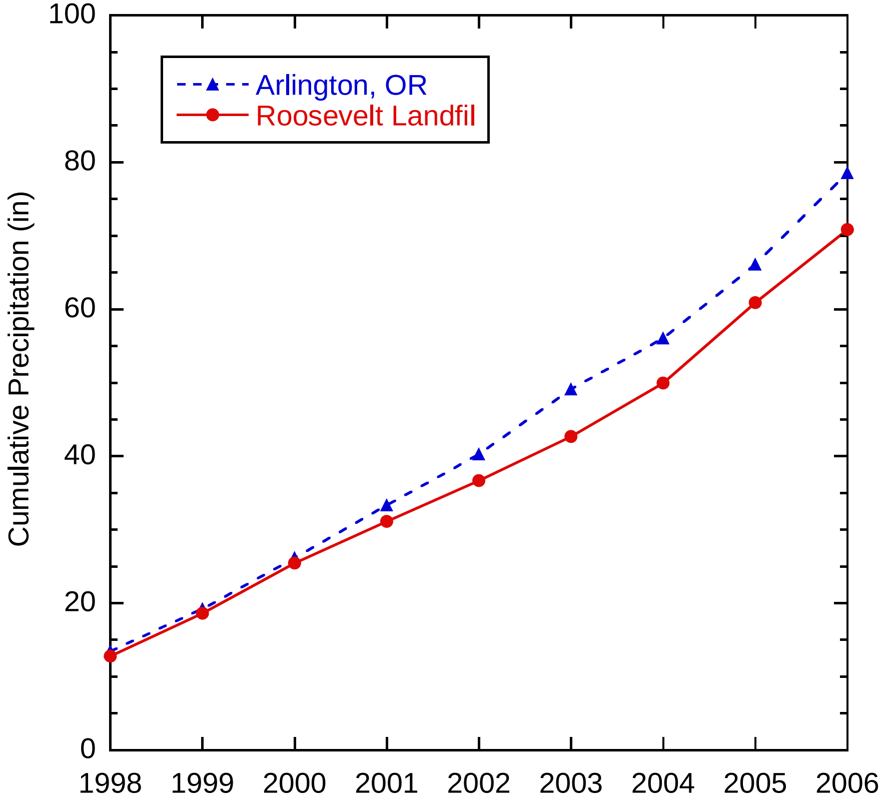
  http://rredc.nrel.gov/solar/old_data/nsrdb/

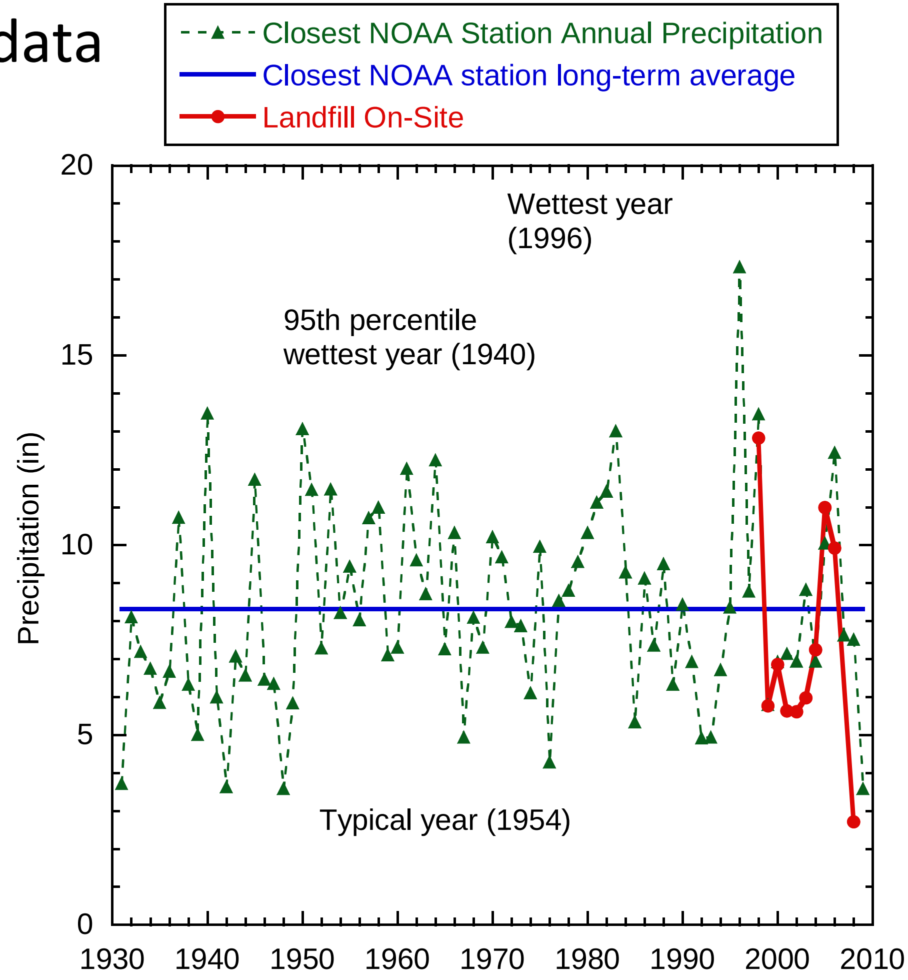
Incomplete Precipitation Data

- Find meteorological station as close to site as practical.
- Compare on-site or local incomplete data with more detailed data from another meteorological station.
  - Station data has higher precipitation, use as is as surrogate or replacement for missing data
  - Station data has lower precipitation, determine scaling factor (average annual, seasonal, monthly) and increase proportionally.
- If necessary, test surrogate data by conducting comparative simulations using actual and surrogate data for period during which both available.

Precipitation – Surrogate Data Example

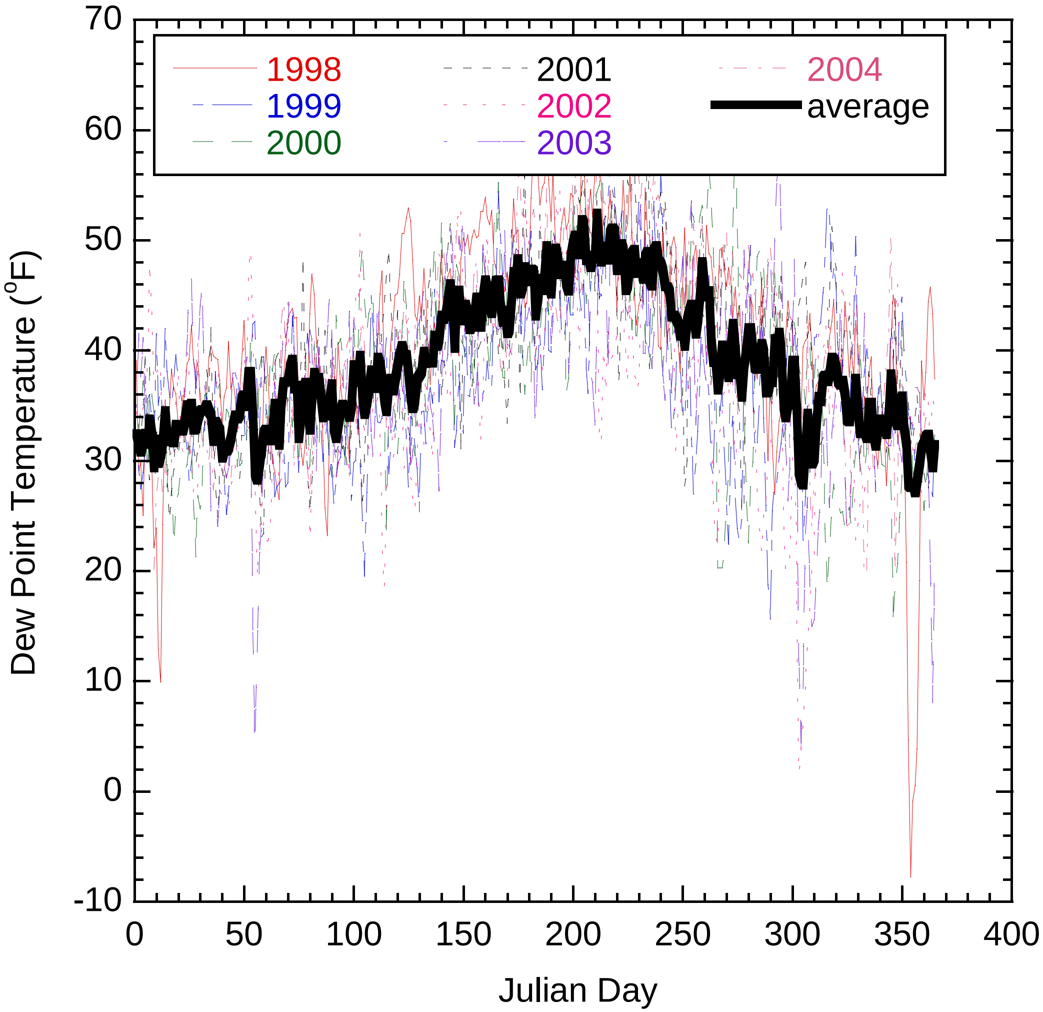
Western case history – on site data available for 8 yr.





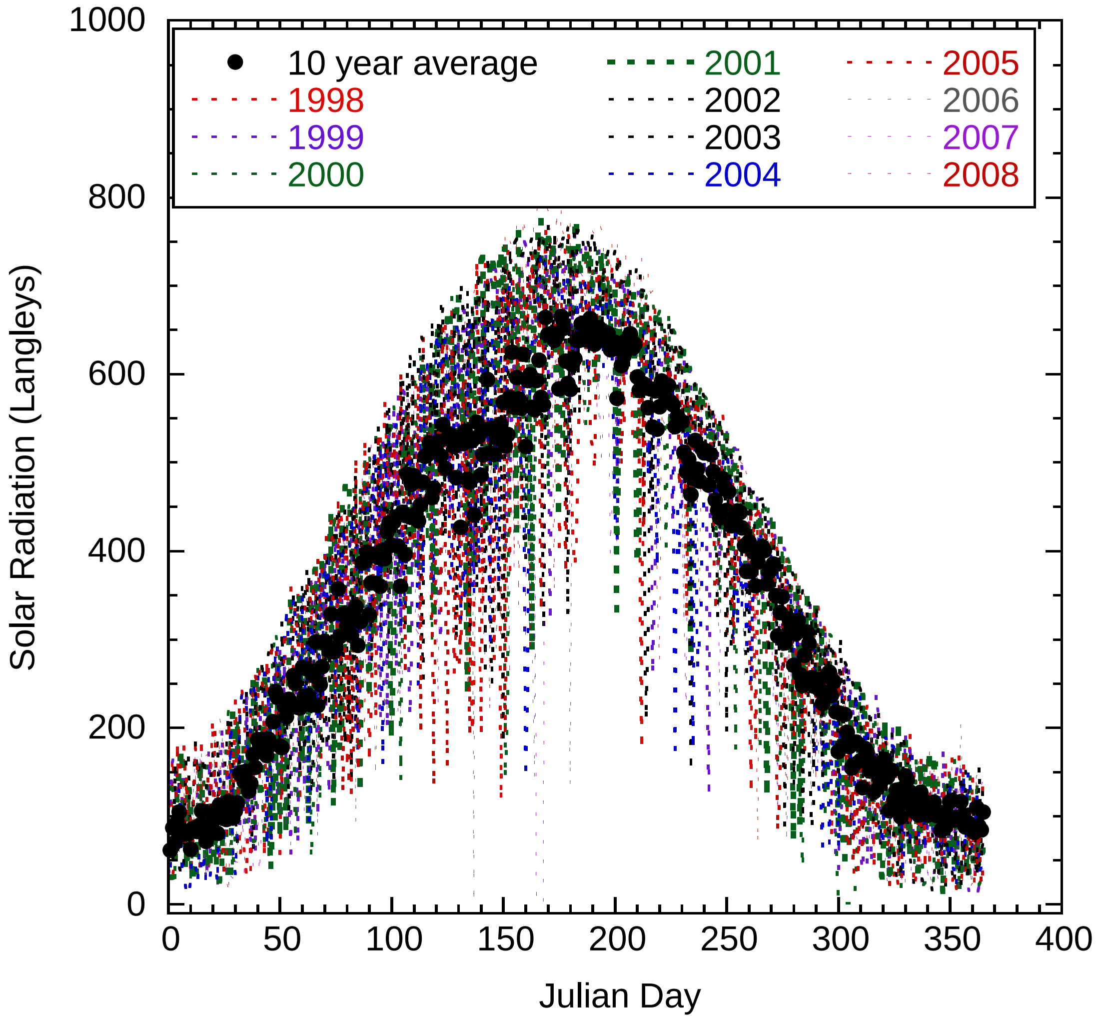
Surrogate site consistently has more precipitation. Use surrogate data in lieu of site specific data.

Humidity Data



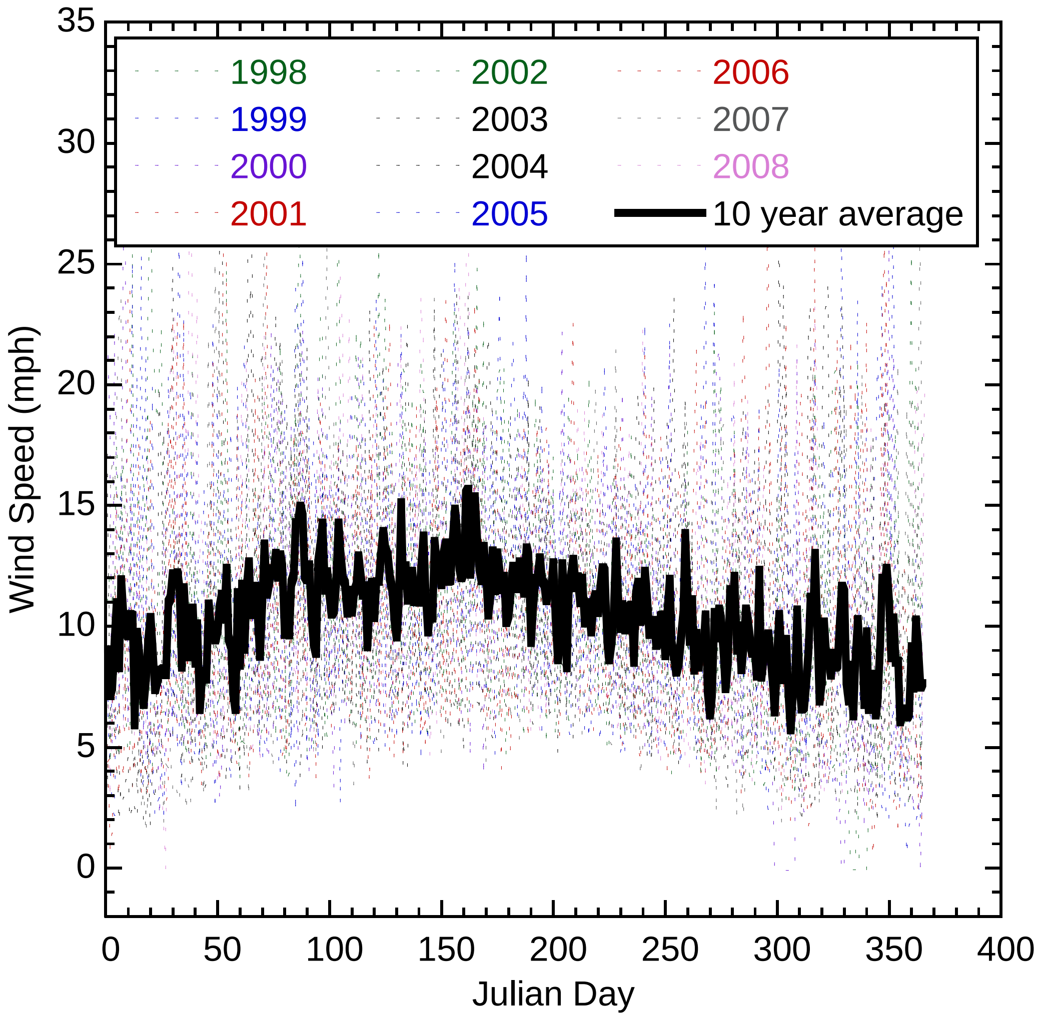
- No long-term data for humidity. Use on-site data, but short record.
- Humidity well-behaved temporally.
- Use daily mean record as surrogate for missing data.

Solar Radiation Data



- No nearby data for solar radiation.
- Solar is very well behaved. Mean trend tends to be biased low, except in fall.
- Use daily mean record as surrogate.

Wind Speed Data



- No nearby data for wind speed radiation.
- Wind is well behaved. Mean trend tends to be biased low (misses highs more than lows), conservative.
- Use daily mean record as surrogate.

Dew Point and Relative Humidity

- Dew point temperature (T_d) is temperature at which water vapor would be saturated. The vapor pressure (kPa) at dew point (°C) is:

$$e = 0.611 \exp\left[\frac{17.27\, T_d}{T_d + 237.3}\right]$$

- The saturated vapor pressure at existing temperature T is:

$$e_s = 0.611 \exp\left[\frac{17.27\, T}{T + 237.3}\right]$$

- The relative humidity, RH = 100 x (e/e_s)

Cloud Cover Fractions (c)

- Overcast: 1.0
- Broken: 0.6-0.9
- Scattered: 0.4 to 0.6
- Few: 0.1-0.4
- Clear: 0.0

Plant Properties Required for Input

- Growing season (start, end)
- Leaf area index vs. time
- Plant water stress parameters
  - Anerobiosis point
  - Limiting point
  - Wilting point
- Coverage (% bare area)
- Root depth and density function
- Root growth/extension vs. time

Where to Find Plant Properties

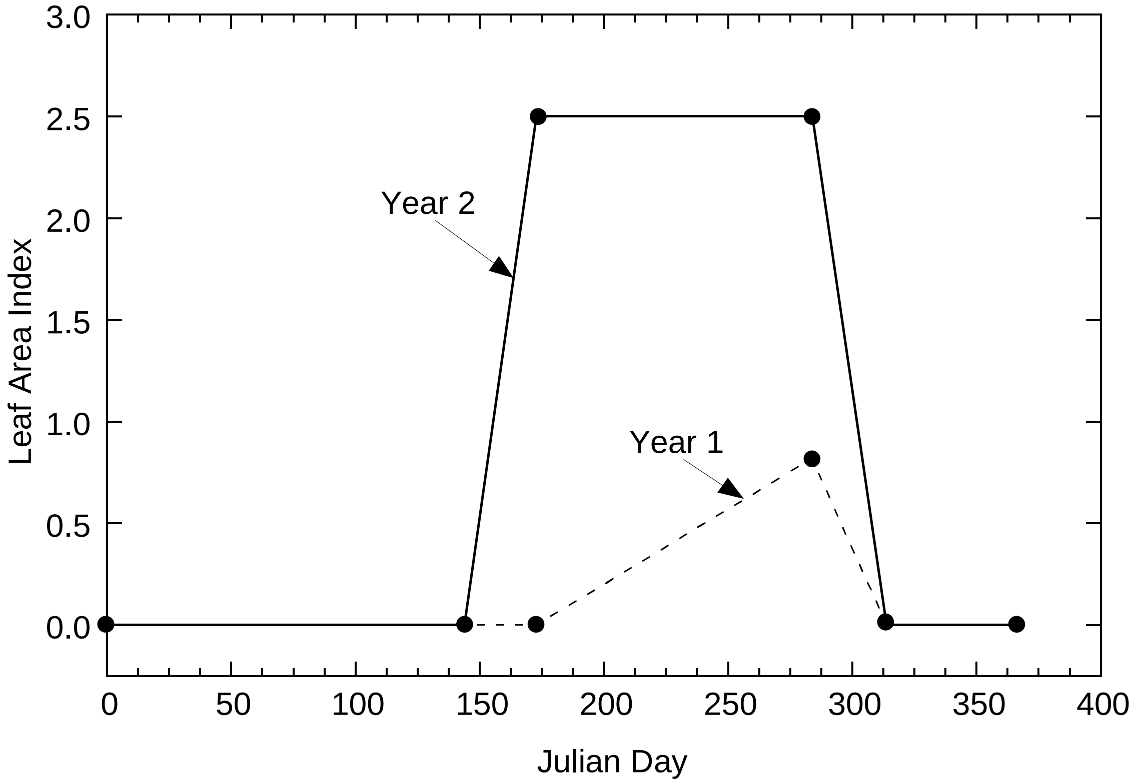
- US Natural Resources Conservation Service (NRCS)

  Home: http://www.nrcs.usda.gov/

  Plants Database: http://plants.usda.gov/

- Winkler Database (1999) https://mywebspace.wisc.edu/chbenson/Winkler/

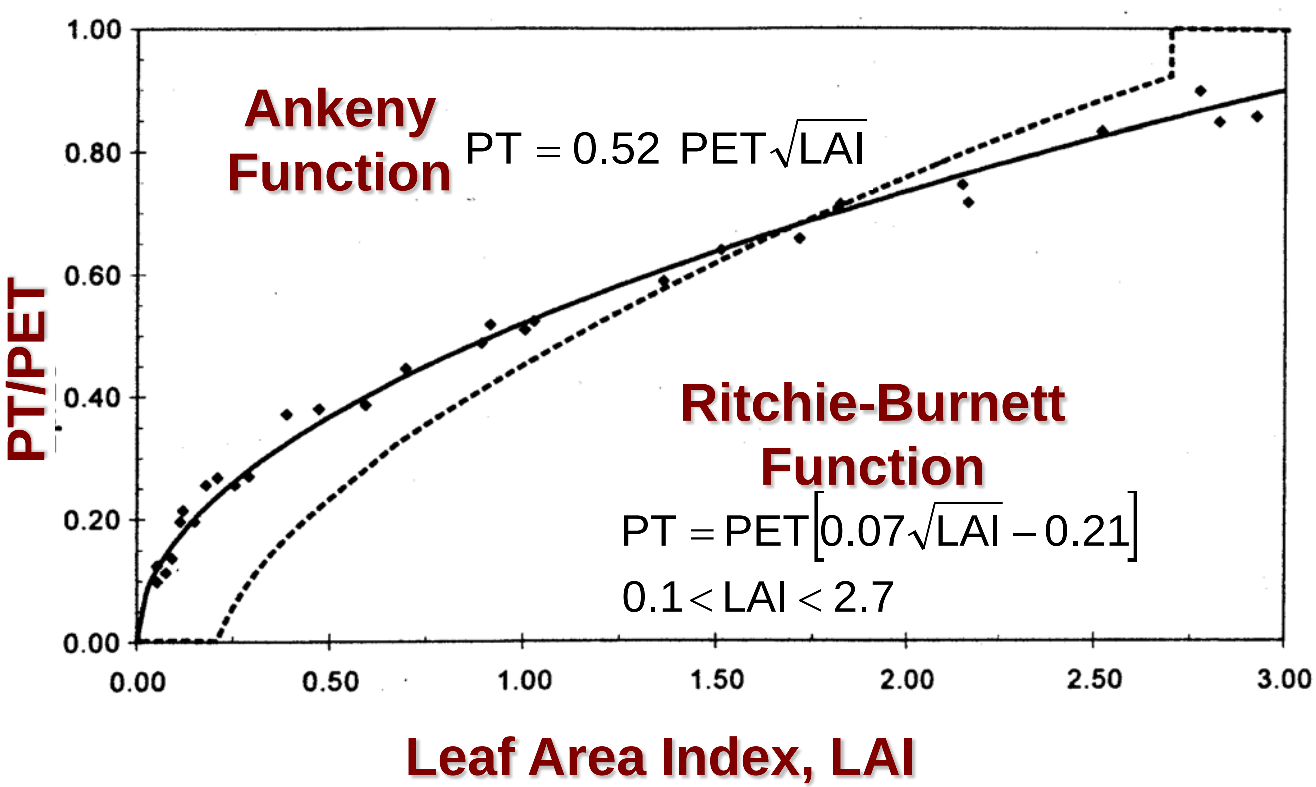
LAI vs. Time



- Use approximate linear function
- Ramp up to peak linearly during first 30 d.
- Ramp down to zero during final 30 d
- Maintain constant LAI between.

Partitioning of PE and PT from LAI

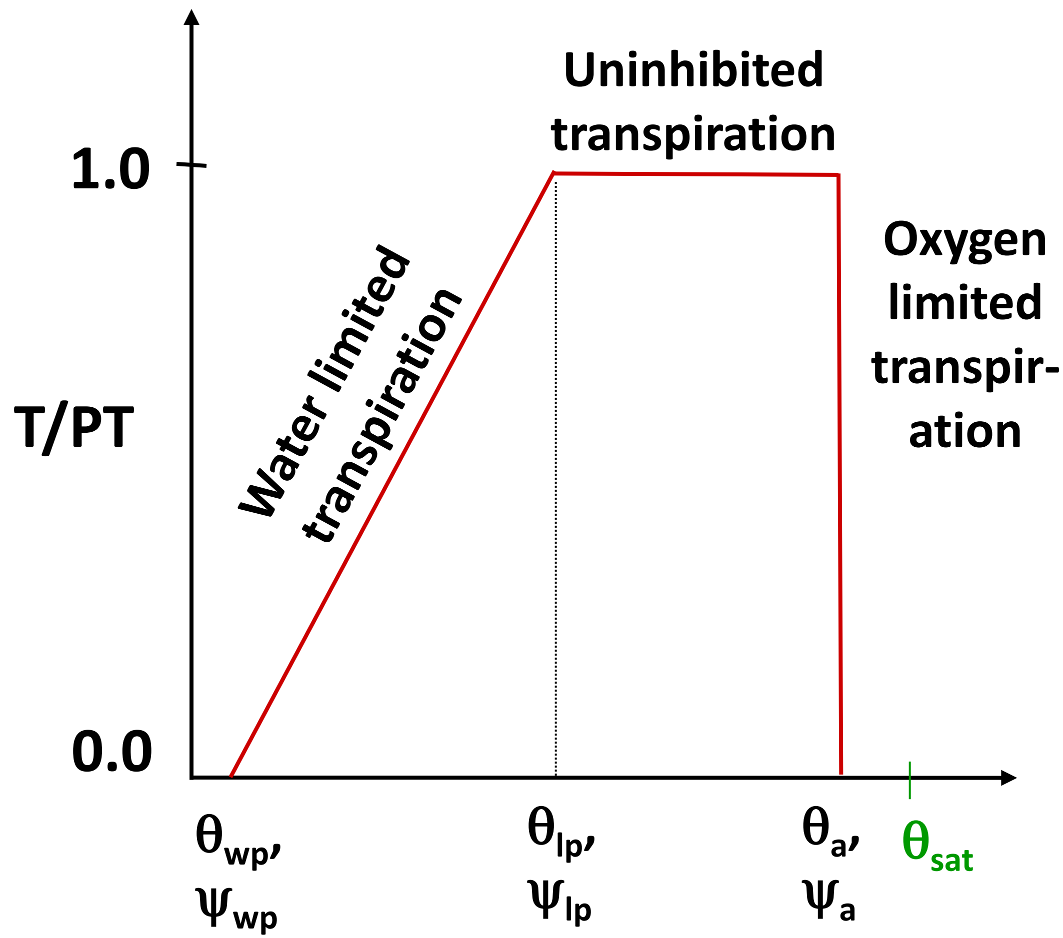
PET to PE-PT Partitioning Used in Most Models



$PT + PE = PET$

- PT-PE split sensitive when LAI < 0.5
- Modest sensitivity for LAI > 0.5

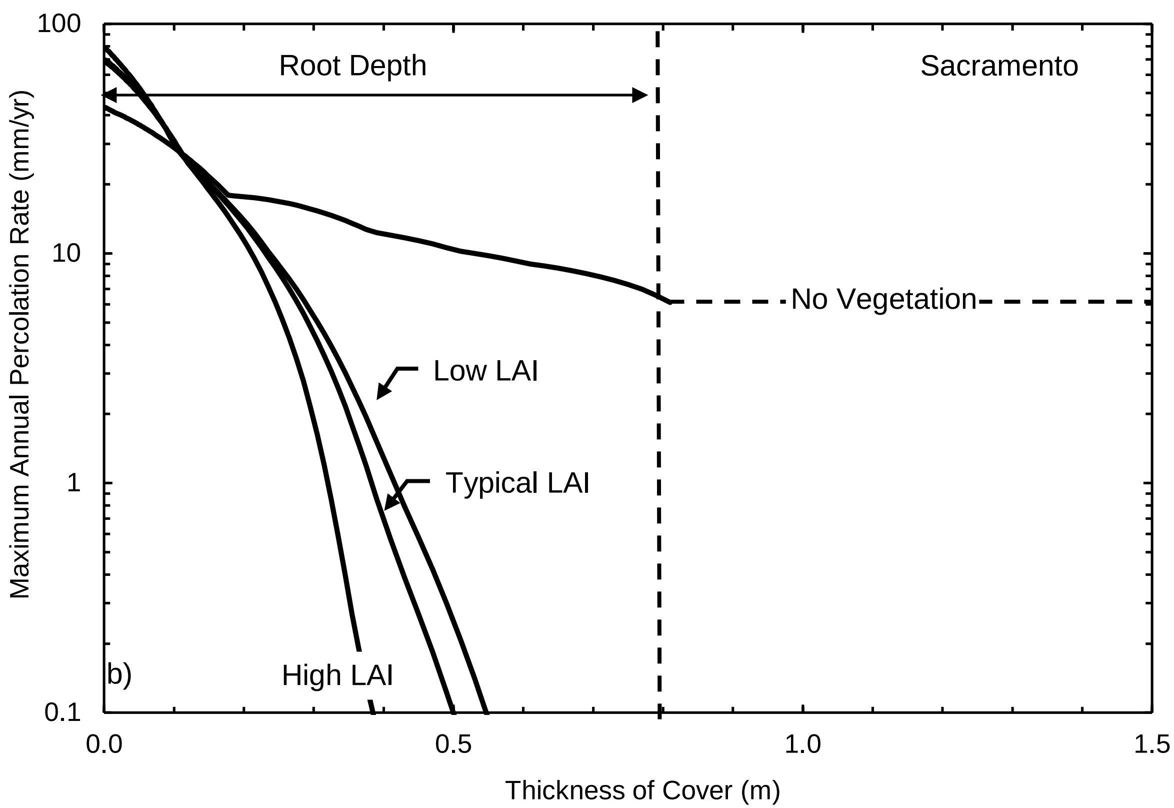
Water Stress and Plant Limiting Function



- Anerobiosis point:
  1-5 kPa
- Limiting point:
  - Humid: 0.8 MPa
  - Arid: 1-2 MPa
- Wilting point:
  - Humid: 1.5 MPa
  - Arid: 4-6 MPa

Sensitivity to Leaf Area Index

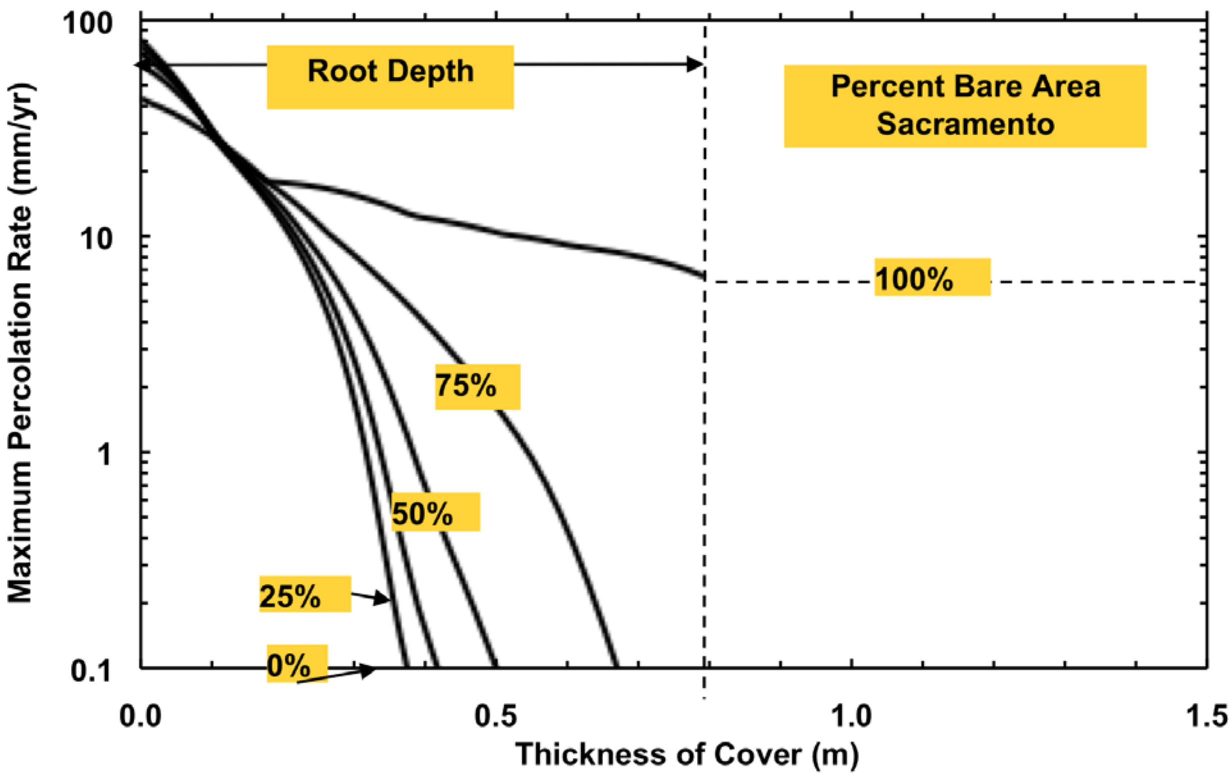
Maximum Percolation Rate for
Wettest Year Repeated 5x



- LAI Used
  - Low = 0.7
  - Med = 1.4
  - High = 5.2
- Not particularly sensitive for reasonable LAI.

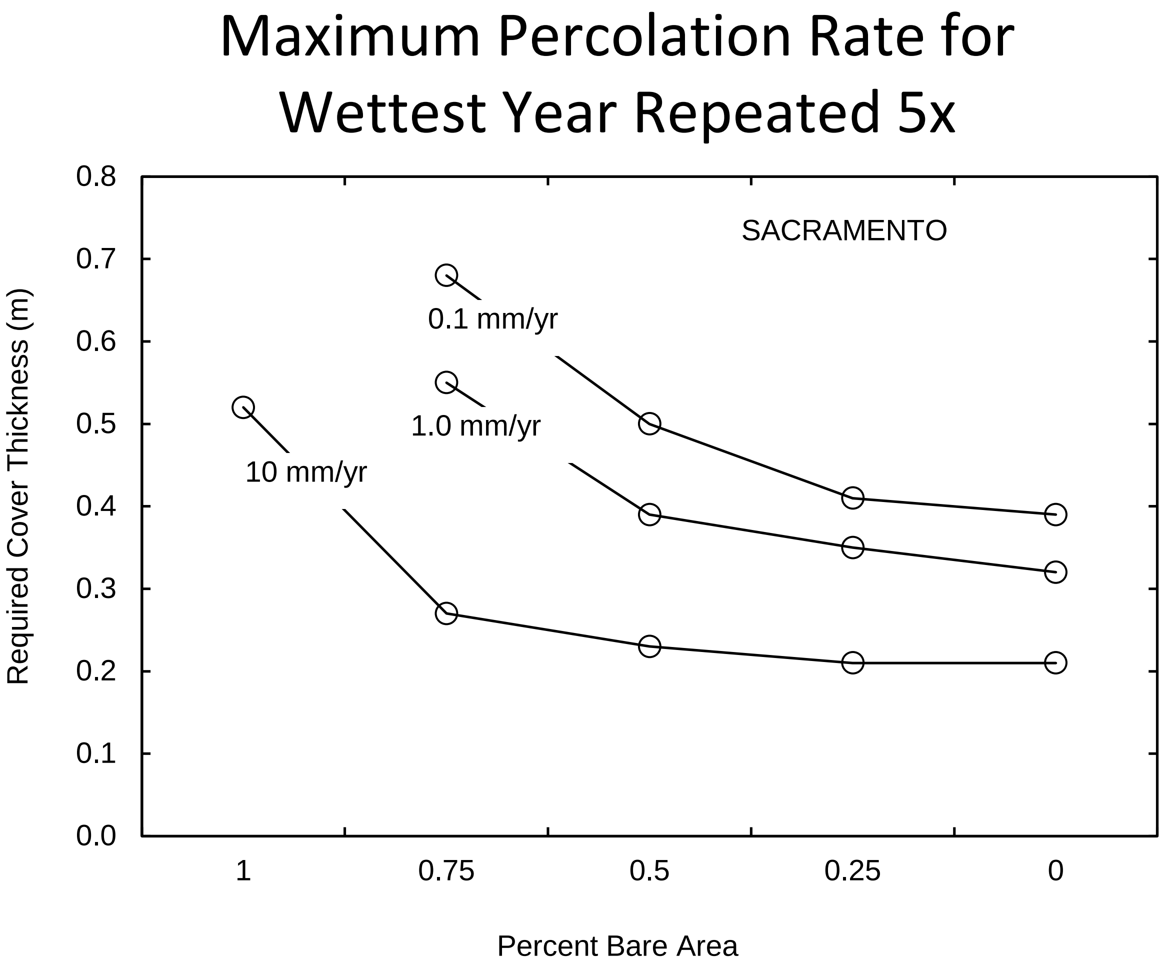
Sensitivity to Coverage (or Bare Area)

Maximum Percolation Rate for
Wettest Year Repeated 5x



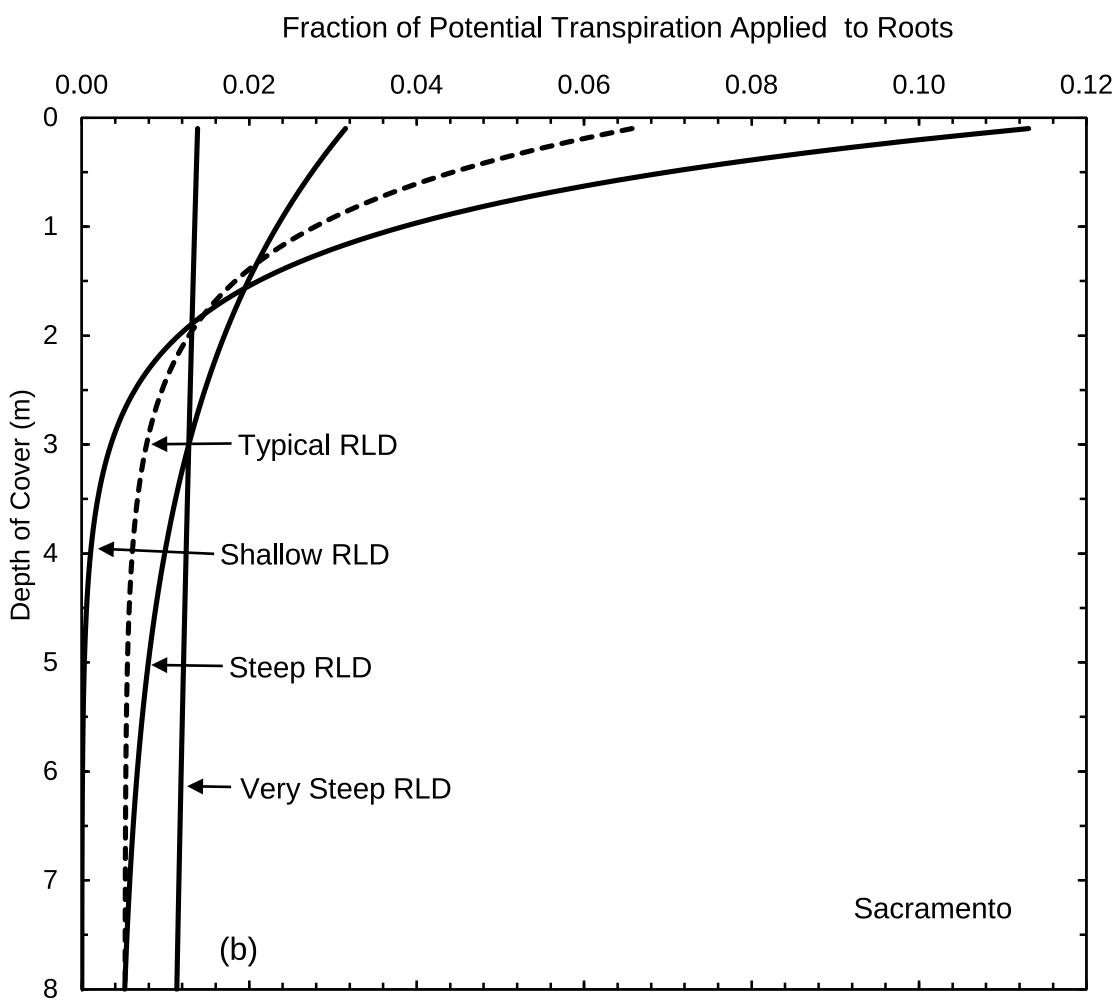
- Little sensitivity when coverage > 50%
- Modest sensitivity when coverage is 25-50%.
- Bare area = 100 - % coverage.

Sensitivity to Coverage (or Bare Area)



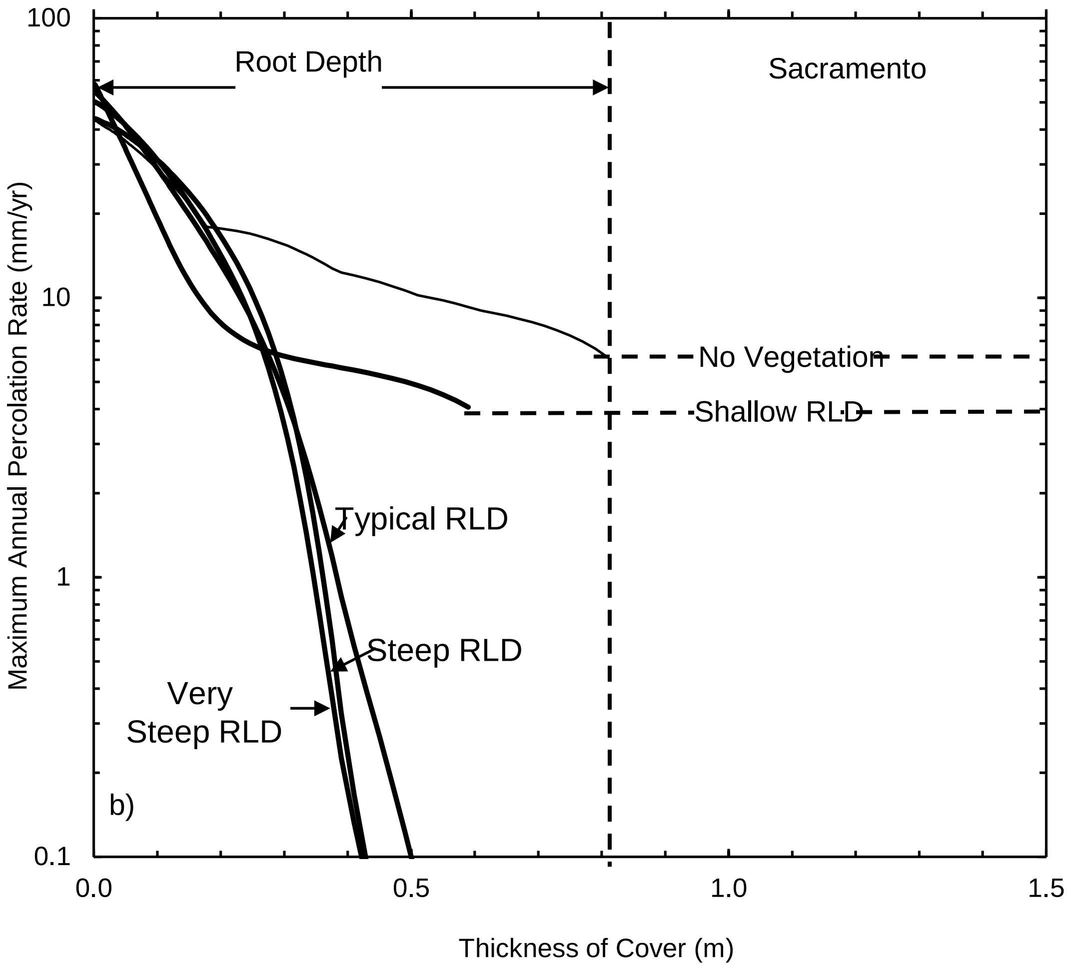
- Sensitivity increases as required percolation rate diminishes
- Low to modest sensitivity when coverage > 50% (Bare area > 50%).

Sensitivity to Root Depth & Density Function



- PET partitioned into PE & PT. PT applied to roots in proportion to density.
- Shallower RLD applies more PT to shallow depths.

Sensitivity to Root Depth & Density Function



- Not very sensitive to RLD provided roots extend through depth of cover.
- Using typical RLD from Winkler acceptable.

Summary Remarks on Plant Properties

- Predictions more sensitive to presence of vegetation than details of vegetation.
- Reflects simplicity of vegetation algorithms rather than importance of vegetation.
- Can use typical properties without too much error.

Measuring Plant Parameters

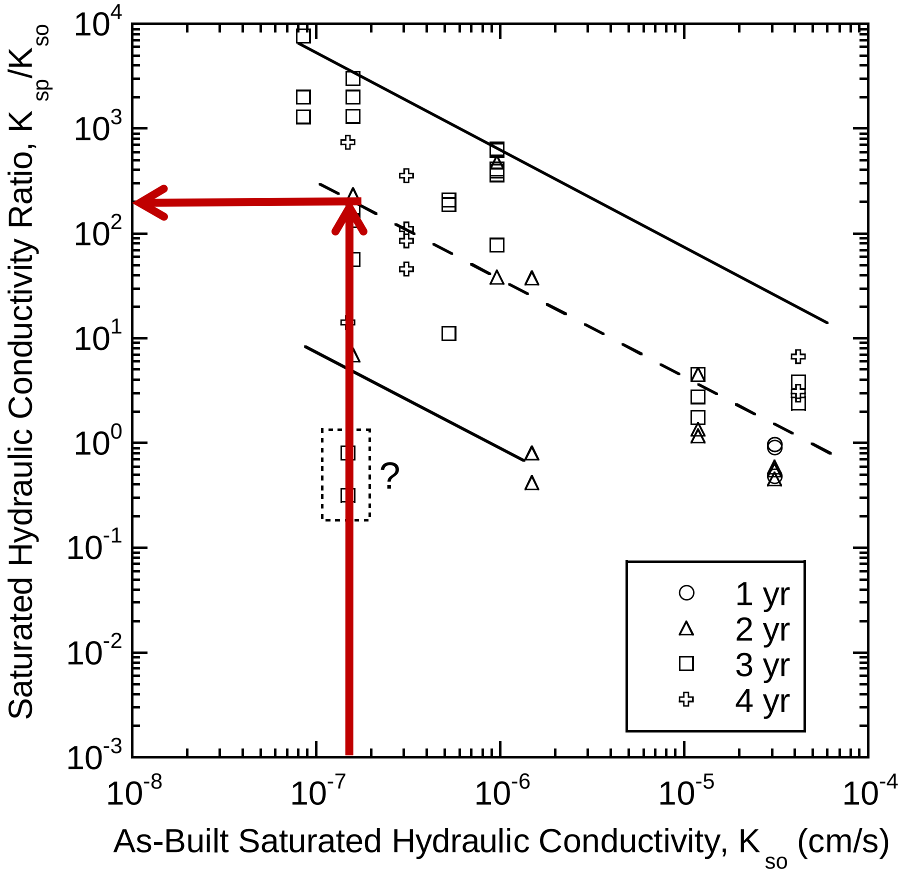
- Select analog site with similar soils and vegetation
- Evaluate distribution of species and coverage (plant ecologist provide support)
- Measure LAI as a function of time
- Measure RLD
- Measure wilting point

Benson, C., Thorstad, P., Jo, H., and Rock, S. (2007), Hydraulic Performance of Geosynthetic Clay Liners in a Landfill Final Cover, *J. Geotech. and Geoenvironmental Eng.*, 133(7), 814-827.

Soil Hydraulic Properties

- Saturated hydraulic conductivity: usually in 10^{-5} cm/s range for storage layer at depths below 300 mm. Shallower 10^{-3} to 10^{-4} cm/s
- van Genuchten's α: 0.01 to 0.1 kPa^{-1}
- van Genuchten's n: 1.2 to 1.4
- Saturated water content, θ_s: 0.35 to 0.45 ($\gamma_d \approx$ 15.5 kN/m^3)
- Residual water content, θ_r: set at zero, < 0.05
- Pore interaction term:
  - clean coarse soils = 0.5
  - fine-textured soils for storage layer = -2

Accounting for Pedogenesis - K_s



From lab, $K_s = 1.5 \times 10^{-7}$ cm/s

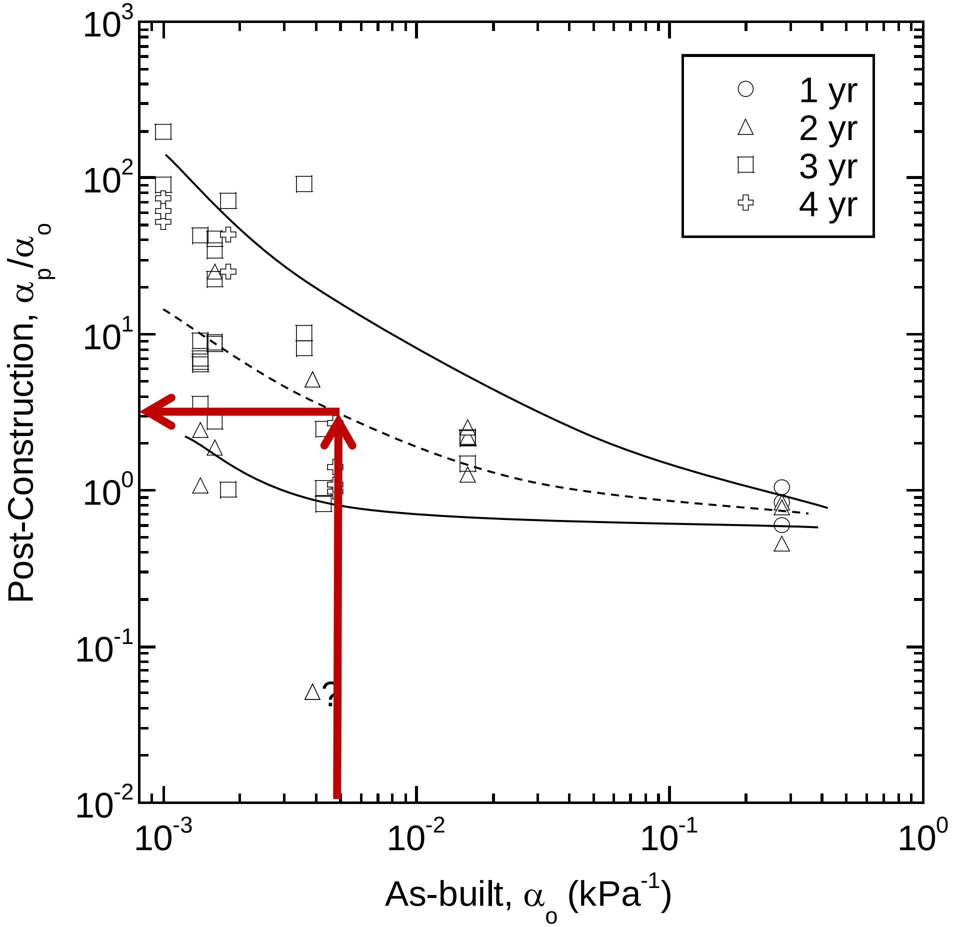
$K_{sp}/K_{so} = 200$

$K_{sp} = 200 \times 1.5 \times 10^{-7}$

$K_{sp} = 3.0 \times 10^{-5}$ cm/s

Benson, C., Sawangsuriya, A., Trzebiatowski, B., and Albright, W. (2007), Post-Construction Changes in the Hydraulic Properties of Water Balance Cover Soils, *J. Geotech. and Geoenvironmental Eng.*, 133(4), 349-359.

Accounting for Pedogenesis - α



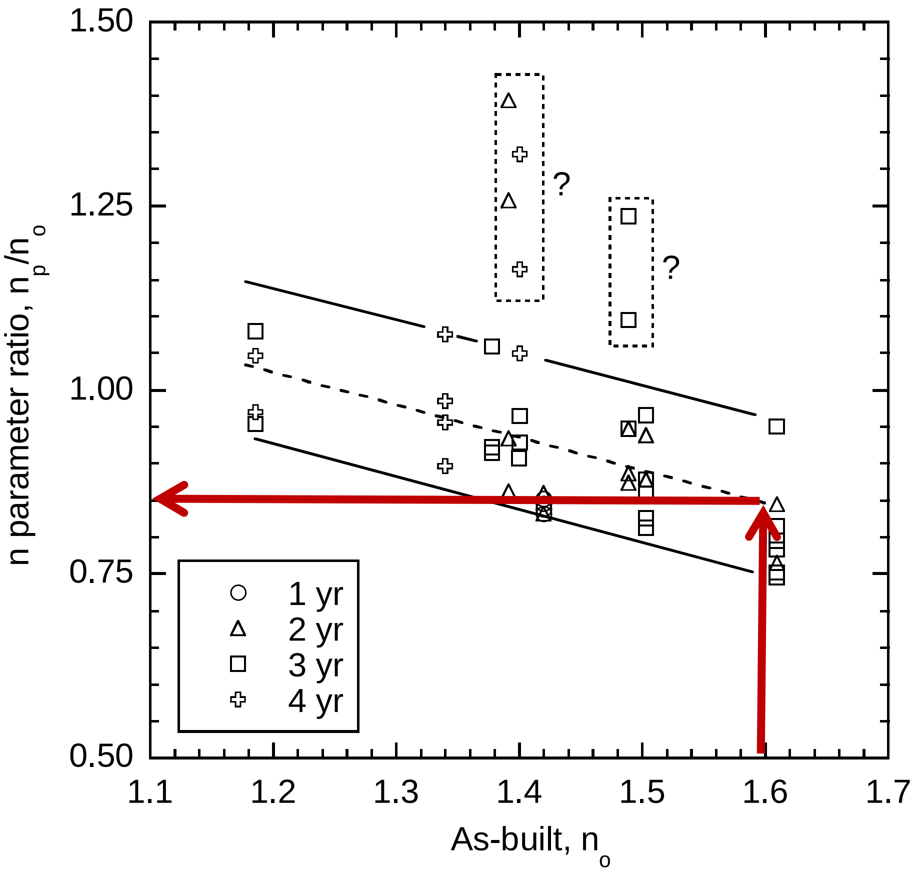
From lab, α = 0.005 kPa^{-1}

$\alpha_p/\alpha_o = 3.1$

$\alpha_p = 3.1 \times 0.005$

$\alpha_p = 0.016$ kPa^{-1}

Accounting for Pedogenesis - n



From lab, n = 1.60

$n_p/n_o = 0.85$

$n_p = 0.85 \times 1.60$

$n_p = 1.36$

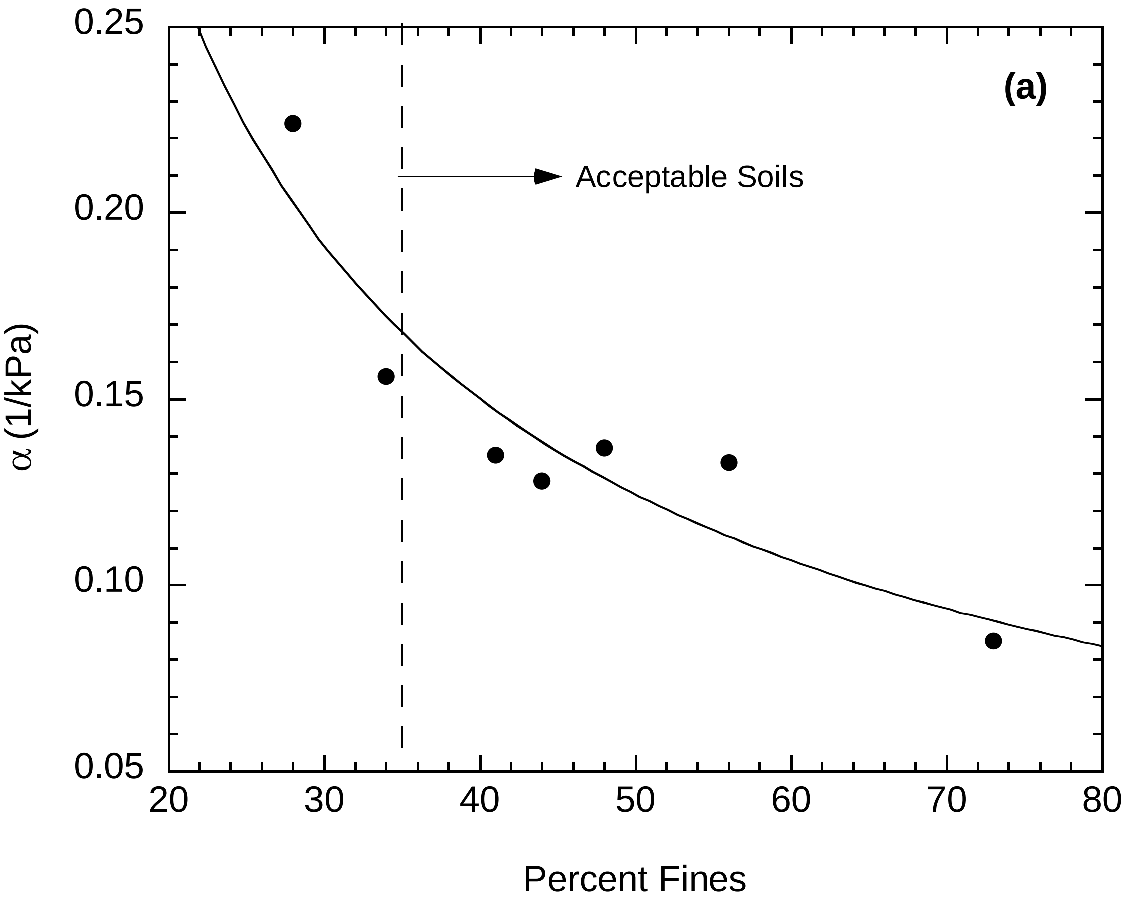
Using Models to Develop QA Requirements

- Evaluated range of samples from borrow source investigation representing range of fines content.

- Developed relationships between SWCC properties and particle size characteristics.

- Ran performance evaluations using each set of hydraulic properties. Identified soils that provided acceptable percolation, and segregated by % fines.

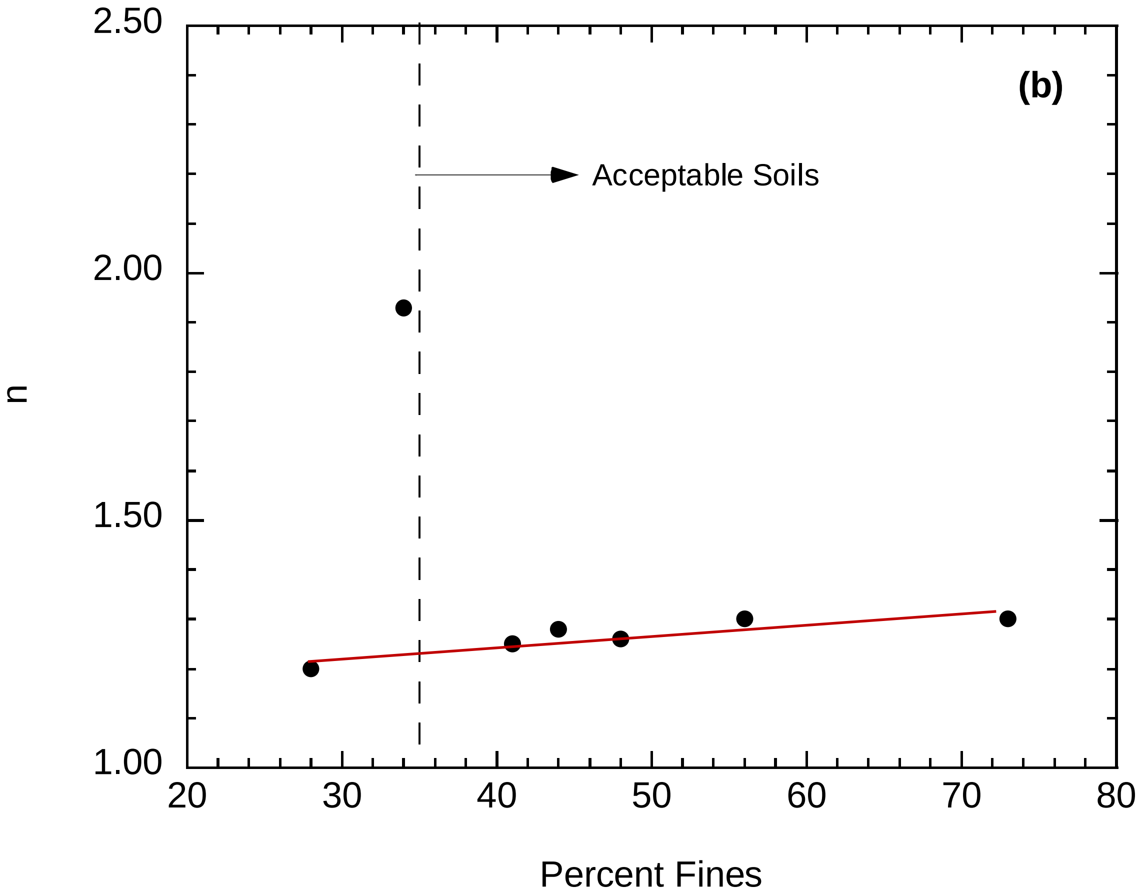
Effect of Fines Content on α



Why is percolation sensitive to α?

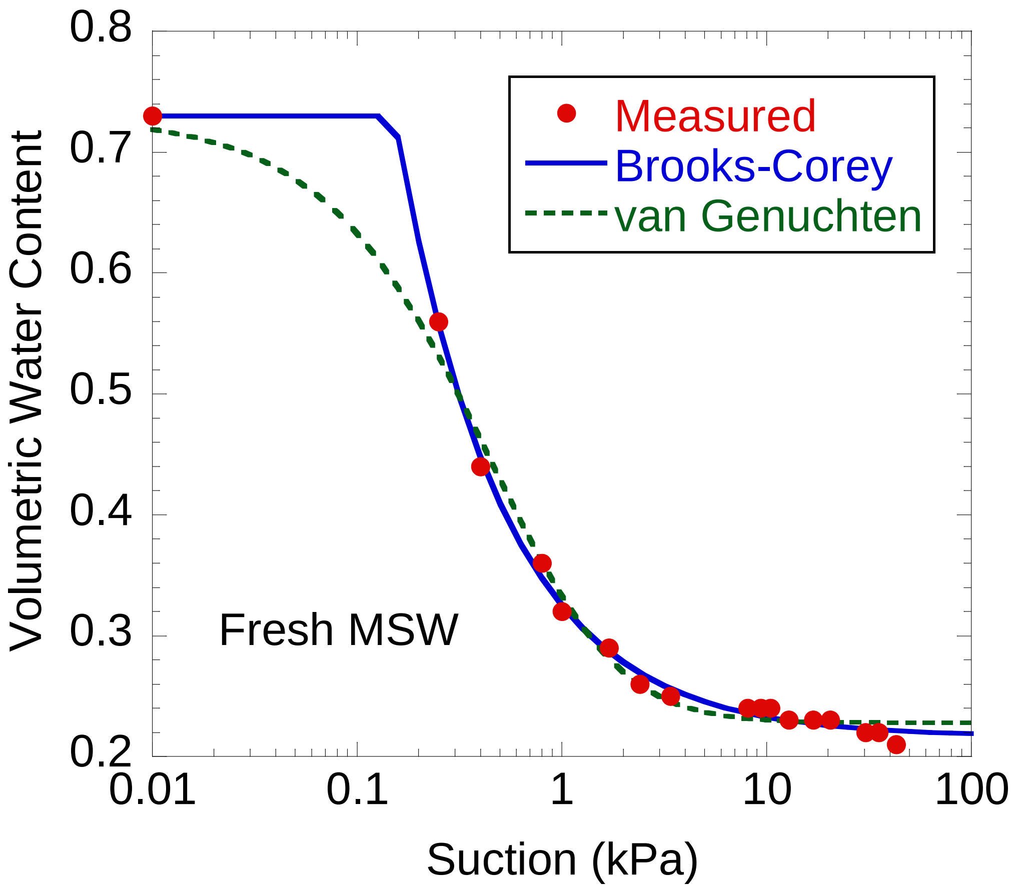
- Evaluated range of samples from borrow source.
- Simulations for design year 5x back to back.
- Found percolation rate was excessive for soils with < 35% fines.

Effect of Fines Content on n



- No significant systematic relationship between n and fines content.
- All but one soil approximately same n.

Waste Hydraulic Properties



Near surface:

- Ks ≈ 10^{-3} to 10^{-1} cm/s
- van Genuchten's α: 5 kPa^{-1}
- van Genuchten's n: 2.0
- $\theta_s = 0.75$, $\theta_r = 0.25$
- Pore interaction term: -1.5

Reality Check: Predictions Consistent with Field Data?

$$\log P_r = 0.33 + 0.0205\,P_a^{1/2} - 0.0018\,(1804 - 2.27\,RH_a) + 0.494\,P_{ss} + 0.111\,P_a^{1/2}\,S_p + 0.0019\,P_a\,P/PET_a - 0.73\,S_a/S_r$$

P_a = annual precipitation

RH_a = annual cumulative relative humidity

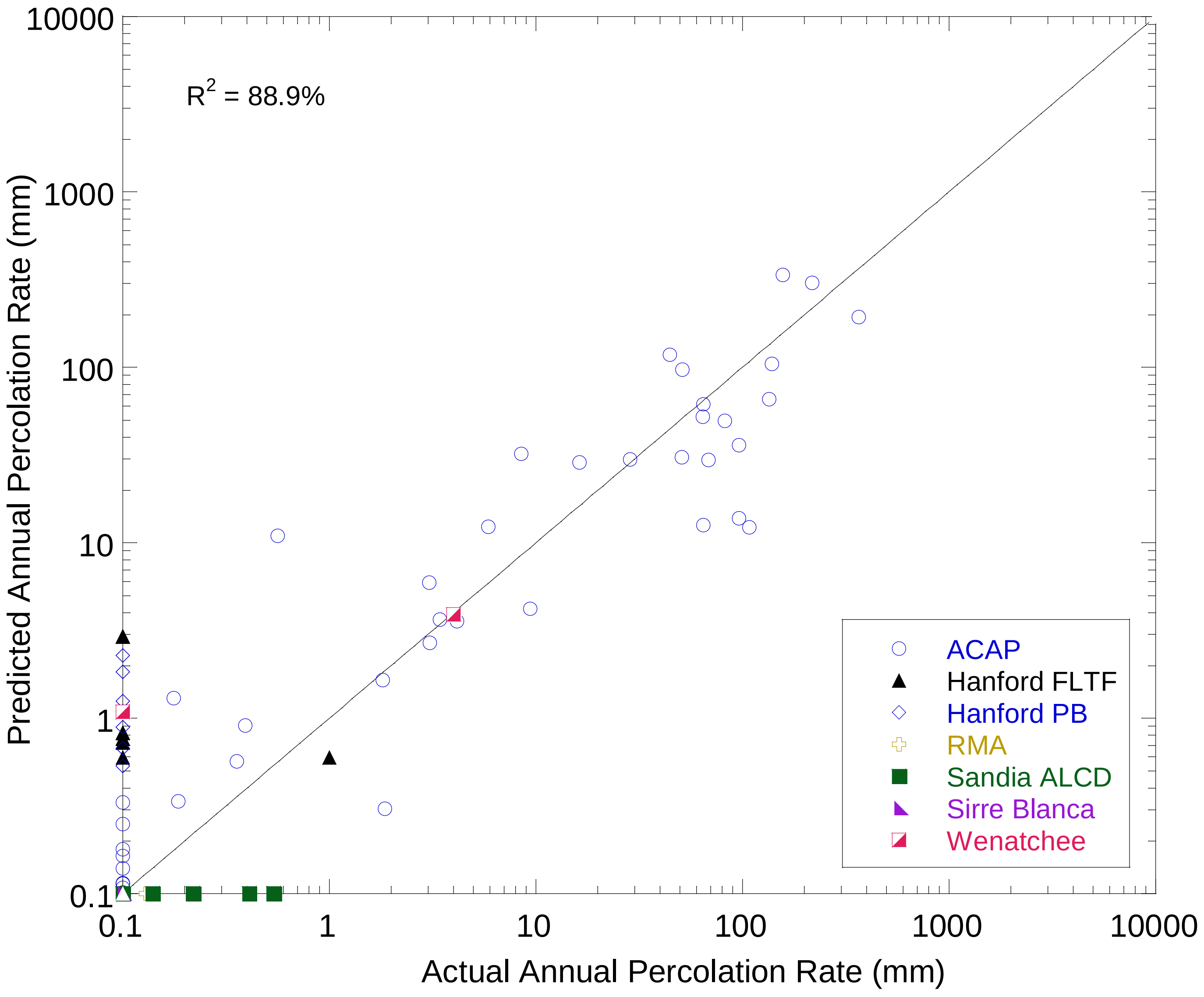
P_{ss} = snow and spring rain (categorical, 1-4)

S_p = seasonality of precipitation (categorical,1 for F-W sites and 0 for S-S sites)

P/PET_a = ratio of annual precip. to annual PET

S_a/S_r = ratio available to required storage capacities

Verification of Regression Model



P_r Predicted from Regression Model (S_a/S_r =1)